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The Thermal Conductivity Of Fire Clay at High Temperatures

PHYSICS

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THE THERMAL CONDUCTIVITY OF FIRE CLAY AT HIGH TEMPERATURES

BY

WILLARD LEO EGY

B. S. University of Illinois, 1907

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THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN PHYSICS

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1909

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UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

May 15, 1909

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

WILLARD LEO EGY

ENTITLED THE THERMAL CONDUCTIVITY OF FIRE CLAY AT HIGH TEMPERATURES

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Physics

A. P. Carman
In Charge of Major Work

A. P. Carman
Head of Department

Recommendation concurred in:

L P Breckenridge

Edward C. Schmidt

Committee
on
Final Examination

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The object in taking up this work was primarily to obtain information concerning the loss of heat thru the walls of boiler furnaces, altho the problem of thermal conductivity is of interest in a number of fields. It is well known that considerable heat escapes thru the walls of furnaces, but no idea of the amount of this heat has been obtained by direct methods. Nor do we have any definite knowledge of the effect of different materials upon the quantity of heat lost in this way. While the engineer knows that less heat is lost thru a thicker wall, he does not know how far he is justified in increasing the thickness of the wall until he gets exact figures on the quantity lost in this way.

Knowing the thermal conductivity (K) of brick, however, with the dimensions of the furnace and the inside and outside temperatures of the walls, the quantity of heat transmitted thru them may be readily calculated. Let us take the specific case of a 210 H.P. Heine boiler of the University of Illinois, working under full load.

The area of walls exposed to the hot gases is about 364 ft.^{2}, and the thickness of the same about twenty inches. The average temperature of the inside of this area was approximately 1400°F, and of the outside, 150°F. If we take the value of K as found for that test piece which was nearest like the brick in the setting; that is, K = .0026, and calculate the heat conducted thru the walls (see formula 1, page 4), we get

$$Q = \frac{.0026 \times .555\ (1400 - 150)}{2.54\ (20)}\ 929(364) \times 3600 \qquad (1)$$

$$Q = 4.34 \times 10^7 \text{ cal. per hr.}$$

or 172000 B.T.U. per hr.

UIUC

(†) Transformation Constants

($ft^2/cm^2 = 929.$; $F°/C° = .555$; $in/cm = 2.54$)

This is about 1.6% of the total heat generated. These figures are only approximations, but they show that with careful measurements the heat lost thru the various parts of the walls may be calculated directly.

The study of thermal conductivity is also of importance in all problems of refrigeration. In the construction of cold storage buildings, a convenient method for testing the various materials that might be used would be of great value, altho, of course working at low temperatures presents a somewhat different problem.

The conductivity of the substances in the earth's crust is also of interest to geologists. The British Association for the Advancement of Science had a committee working for seven years to determine the conductivity of some of the rocks in The British Isles. (see reference No. 3, on last page)

In looking over the investigations of the past we see that thermal conductivity has been one of the favorite problems of the physicists. (References to some of this work are given in the back of this paper.) Nearly all of this work, however, was between the temperatures of melting ice and steam at atmospheric pressure, and in no case were even moderately high temperatures reached.*

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*An account has recently been published of some very excellent work done by Dr. Wilhelm Nusselt on the "Thermal Conductivity of Heat Insulators." Some of his measurements were made at temperatures as high as 550°C.

Engineering, Vol. 87, pp 1 and 2. Jan. 1, 1909.

The work of these men shows that the chief difficulties are to obtain and maintain a high temperature with a known quantity of heat, and to get the correct temperatures in the substance tested. Fortunately the electric heating coil and the thermo-couple enable us to solve both of these problems with comparative ease.

We will review briefly the principles of thermal conductivity.

The quantity of heat, (Q) flowing thru a given wall is proportional to the difference in temperature, $(T_1 - T_2)$ of the two faces. For a given difference of temperature, Q is inversely proportional to the thickness, (r). The heat flowing thru a section of the wall will, of course, be proportional to the area, (A) of that section. Q is necessarily proportional, also to the time, (t) over which measurements are taken. Using these principles we may then write

$$Q' = K \frac{T_1 - T_2}{r} At \text{ ------------- } (1)$$

K is a constant for the given substance at any temperature, and is called the internal thermal conductivity or simply the thermal conductivity of that material. If Q is expressed in calories, $T_1 - T_2$, in centigrade degrees, A, in square centimeters, r, in centimeters, and t, in seconds, K will be in C.G.S. units.

If we now consider a lamina of infinitesimal thickness, dr, the difference of temperature between its faces being dT, for a time, dt

$$Q' = K \frac{T - (T + dT)}{dr} Adt = -KA \frac{dT}{dr} dt \text{ ----- } (2)$$

The expression $\frac{dT}{dr}$ is called the temperature gradient at the point in question, or in other words, the change in temperature per unit thickness. From equation (2) we get

$$K = -\frac{Q}{A} \frac{dr}{dT} \text{ -------------------- } (3)$$

where Q is the heat flowing across the area A in unit time.

From the above expression we see that in order to deter-

mine the thermal conductivity of a substance it is necessary to measure the quantity of heat flowing thru a unit area, and the temperature gradient. The most accurate method of measuring Q is to generate a known quantity of heat by means of an electric heating circuit in such a manner that all the heat generated must flow thru the substance to be tested. If a constant quantity of heat is generated until conditions have reached an equilibrium then the quantity of heat conducted thru the material per second must be equal to the quantity generated per second. This method may be used with a heating coil either in a hollow sphere or in a long cylinder. The latter form was chosen for these tests because of the experimental difficulties arising in the former.

In using this method the assumption is made that there will be no tendency at the middle of the cylinder for the heat to flow longitudinally; that is, the exact amount of heat generated by a centimeter length of the coil, taken at the middle, must flow out thru the corresponding circular section of just one centimeter thickness. To avoid errors from this cause the length of the cylinder must be considerable in comparison with its diameter.

The test pieces were made into cylinders about forty centimeters in length and twelve centimeters in diameter, with a hole thru the center about three and one half centimeters in diameter for the reception of the heating coil. Four longitudinal holes (dd See Fig. 1.) about three millimeters in diameter were made in which thermo-couples could be placed for the measurement of the temperatures.

Now applying equation 3(p 4) to the case of a cylinder, the heat, Q, generated by one centimeter length of the coil in unit

time is expressed by

$$Q = \frac{.2392\ EI}{l}\ \text{cal.}$$

where E, represents volts, I, amperes, and l, the length of the coil in centimeters. The constant, .2394 is the reciprocal of the mechanical equivalent of a calorie expressed in joules or watts. The area perpendicular to the flow of heat at a distance r from the axis is $2\pi r$ per unit length. Substituting for Q and A in equation 3, we have

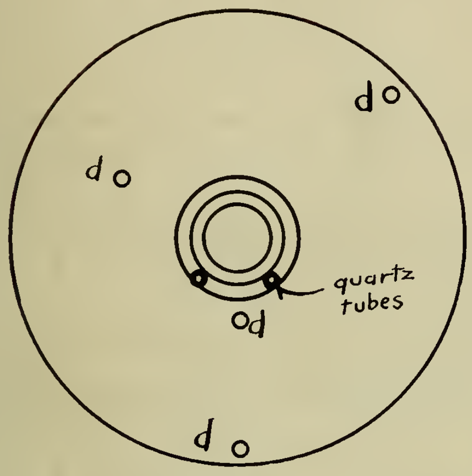


Fig 1.

$$K = -\frac{.2392\ EI}{2\pi l r} \cdot \frac{dr}{dT} \quad . \text{------------} \quad (4)$$

Assuming that K is constant between the temperatures T_1 and T_2, and integrating

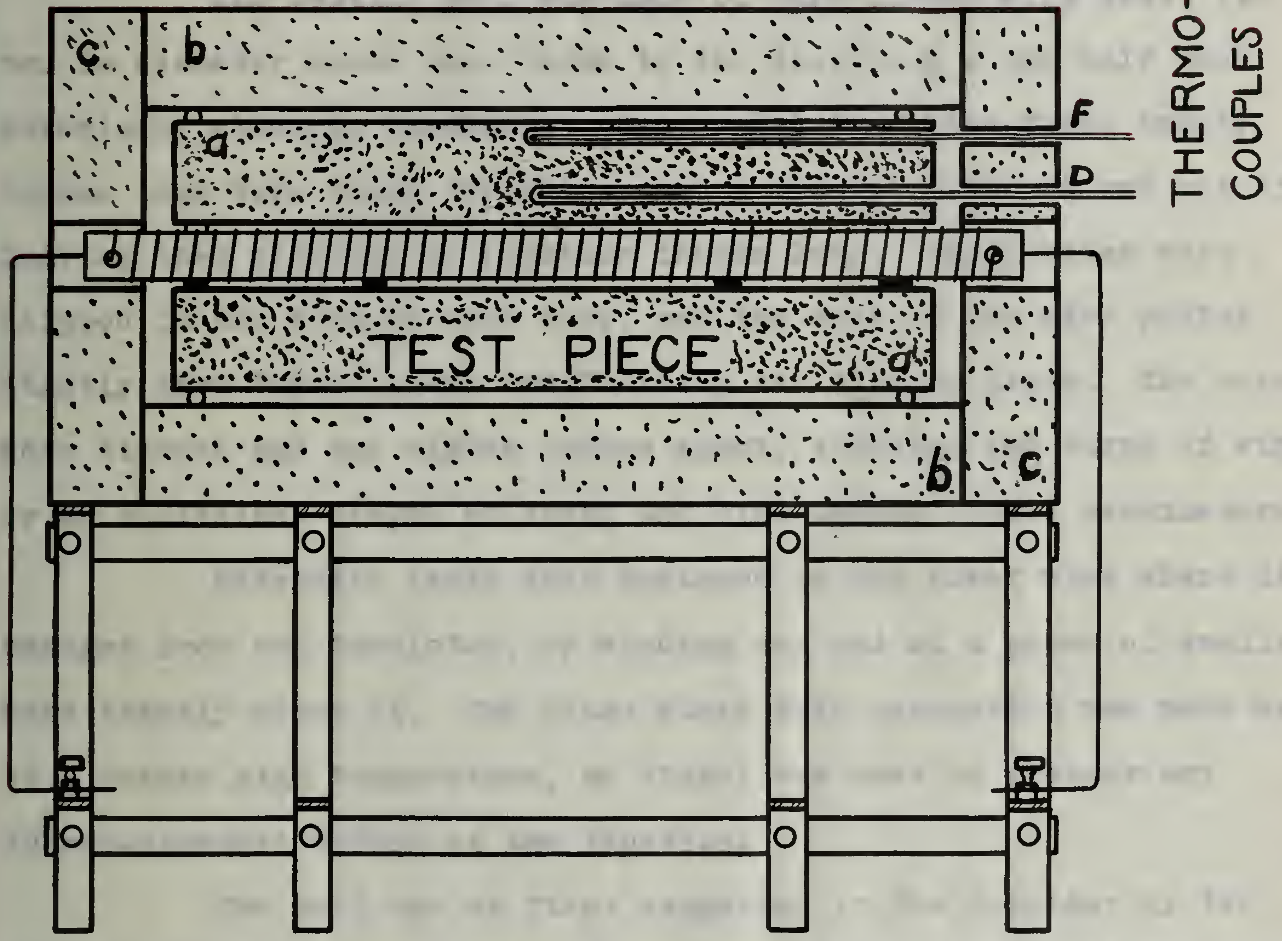
$$K = \frac{.2392}{2\pi l} \cdot \frac{EI}{T_1 - T_2} \log(r_2/r_1) \text{ ------ } (5)$$

where T_1 and T_2 are the temperatures at points distant r_1 and r_2 respectively from the axis. For any given values of r_1 and r_2, the only variables in this equation are EI, the electrical watts dissipated in the coil, and the difference in temperature $(T_1 - T_2)$ between r_1 and r_2. Thus our expression may be reduced to

$$K = C\frac{EI}{T_1 - T_2} \quad \text{------------------} \quad (6)$$

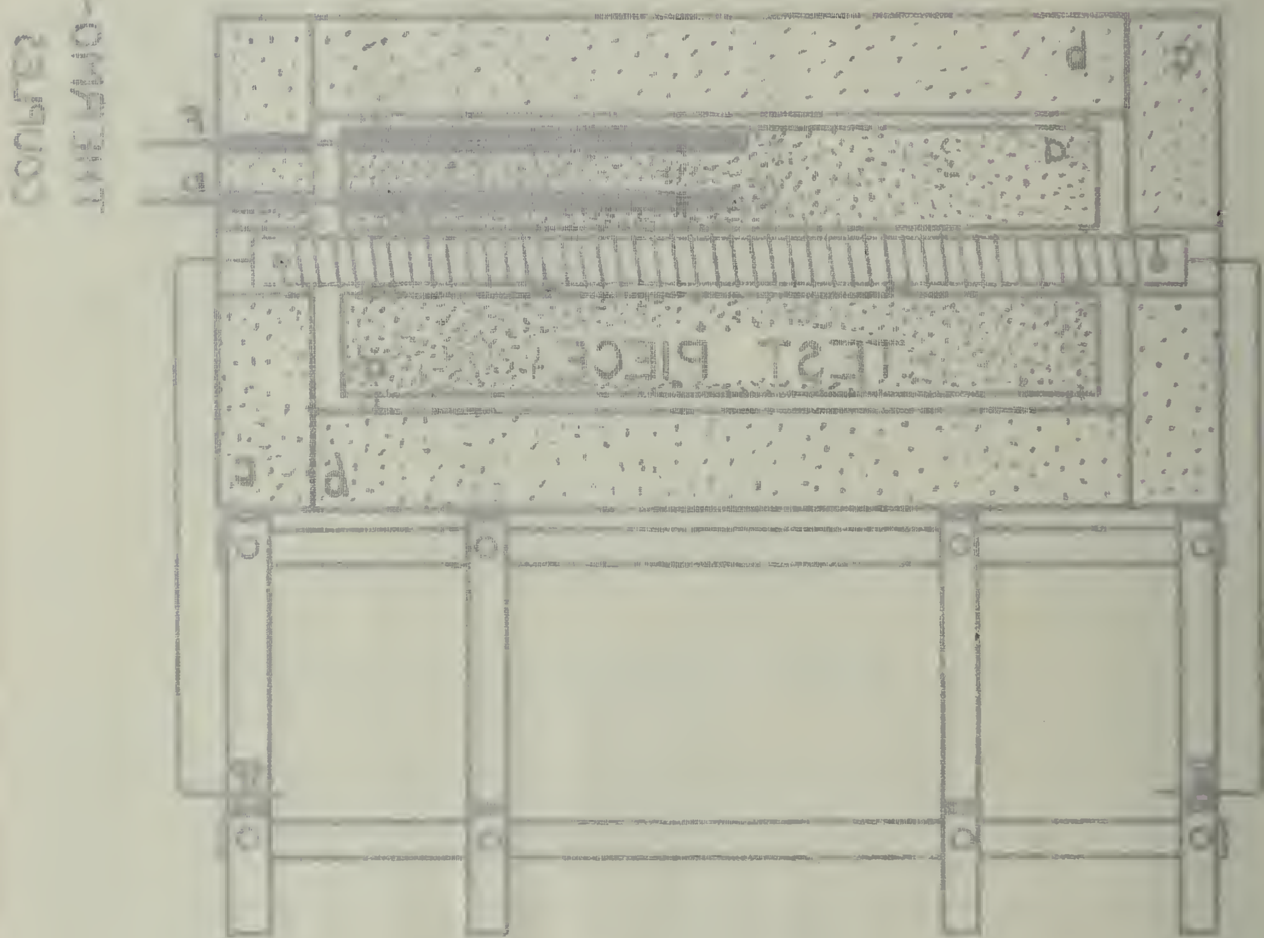
where $C = \dfrac{.2392 \log(r_2/r_1)}{2\pi l}$.

Fig. 2 shows a longitudinal section of the furnace ready for use. aa is the test piece. This was surrounded by a larger cylinder, bb,



SECTION OF FURNACE

FIG. 2.



SECTION OF FURNACE

FIG. 2.

of fireclay in order to get uniform radiation from aa, and also to maintain higher temperatures. Coverings, cc, were placed over each end to prevent loss of heat in this direction. The whole was supported by an open frame-work of strap iron. Two thermo-couples were placed in the holes, D and F.

The heating coil was made of pure nickel wire about 1.8 mm. in diameter wound nine turns to the inch upon a one half inch porcelain, electric insulator. Commercial insulator tubes twenty inches long were taken for this purpose and the enlarged end cut off, leaving them eighteen or nineteen inches long. Small holes were chipped in the ends of each tube, and the ends of the wire pulled tightly thru these holes, thus holding the wire in place. The holes were sixteen and one eighth inches apart, allowing 145 turns of wire, or an equivalent length of forty and nine tenths (40.9) centimeters.

Potential leads were fastened to the power wire where it emerged from the insulator, by winding one end of a piece of smaller wire tightly about it. The place where this connection was made was at a rather high temperature, so nickel was used to prevent any thermo-electric effect at the junction.

The coil was at first supported in the cylinder by two small pieces of quartz tubing at each end (See Fig.1). At the higher temperatures, however, the insulator softened and sagged down in the middle, and two additional pieces of quartz were placed under it one third the distance from the ends. The holes in the end of the furnace were packed with asbestos to prevent the escape of heat. The heating coil was made a few turns longer than the test piece to prevent cooling of the ends.

The current was measured by a Weston Direct reading Port-

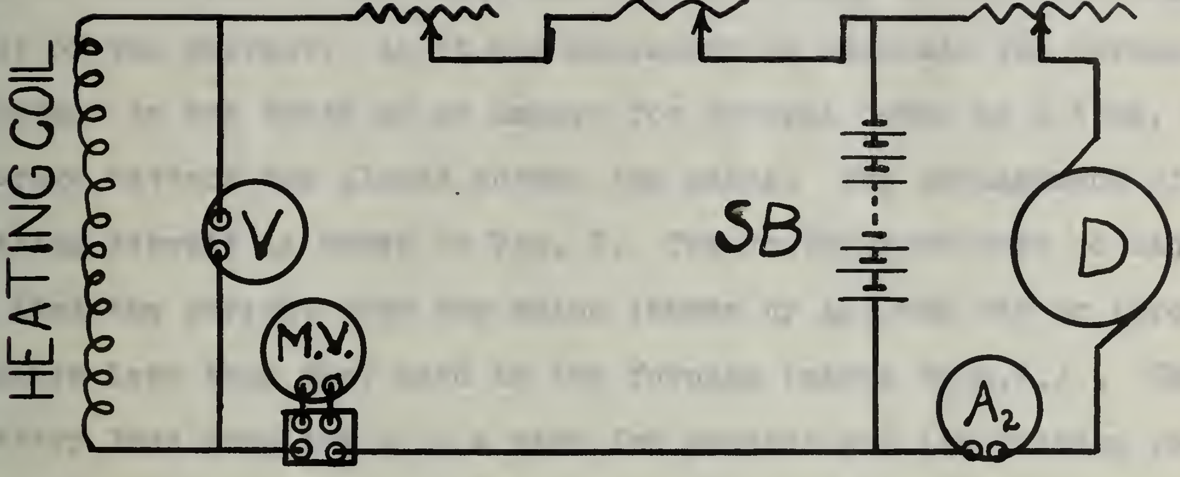


FIG. 3.

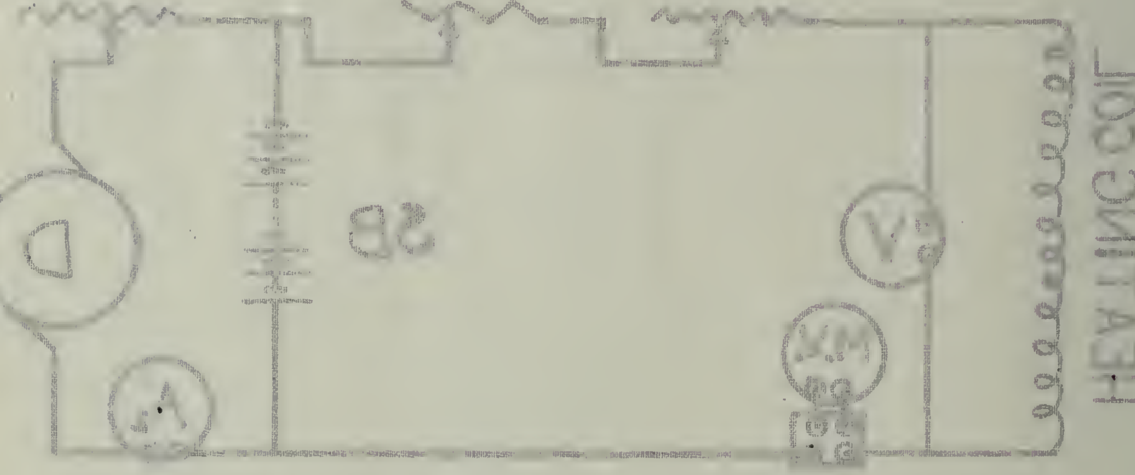


FIG.3.

able Standard Millivoltmeter and shunt. The current was taken from 110 volt mains and was regulated by means of two large rheostats. One of these was of low resistance which allowed a very fine adjustment of the current. As it was necessary to maintain the current constant to one tenth of an ampere for several hours at a time, a storage battery was placed across the mains. The arrangement of the heating circuit is shown in Fig. 3. The resistances were so adjusted that the current from the mains (shown by A_2) was two or three amperes less than that used in the furnace (shown by M.V.) . The battery thus supplied only a very few amperes and its voltage remained very constant even tho the line voltage changed considerably.

The voltage drop thru the coil was measured by a Weston portable voltmeter, the smallest divisions of which corresponded to one volt.

The temperature coefficient of nickel is very large and the resistance of the wire varied considerably with the temperature. As the turns at the end of the coil were somewhat cooler than those in the middle, their resistance would be less, and the average voltage drop per centimeter for the whole coil would be less than that of the central portion. As the average value was used in the calculations, an error would thus be introduced. This was compensated for by having the potential leads connected to the heating circuit, as stated above, outside the insulator, thus adding to the potential drop across the actual 145 turns, the drop in the wire from the last turn to the point of connection.

The temperatures were measured by platinum, platinum-rhodium thermo-couples. The couples were made by Heraus in Germany. These couples were calibrated by the melting point method, using

zinc, silver, and copper. The melting points of these metals were taken as 419°, 961.5°, and 1084°C, respectively, which are the values found by Holborn and Day (1900) and are accepted by the German Reichsanstalt.

The electro-motive force of the couples was assumed to follow the law $T = A + BE + CE^2$, where T represents temperature and E, electro-motive force. The couples were also calibrated in opposition as a differential couple. This was done by placing both couples in a quartz tube in a large piece of iron and heating the iron up to about 1100°C, taking the reading of the differential couple at various temperatures.

The couples were placed in the small holes (~~dd~~ DF Fig. 2.) in the test piece far enough that the junctions were midway between the ends. The two wires were insulated from each other by placing very small porcelain tubing over the platinum-rhodium wire. The other ends of the couples were soldered to copper wires, and these junctions kept at a temperature of 0°C. This was done by placing the junction in a small glass tube, closed at the lower end, which was placed thru the lid of a double walled vessel containing ice and water. The copper wire was surrounded by capillary glass tubing to insulate the wires from each other in the larger tube.

The electro-motive force of the couples was measured by a Wolff potentiometer and a galvanometer using the zero method. Each couple was read separately and then the two were connected in opposition and read as a differential couple. The relation between this reading and the corresponding difference in temperature is obtained as follows. Let us call these readings ΔE. Let the curve DD(Fig.4) represent the relation between temperature and electromotive force

for couple D, and curve FF, that for couple F. Let E_1 and E_2 be the readings of couples D and F respectively. The curve DD is expressed by the equation

$$T_1 = A + BE_1 + CE_1^2$$

$$\text{and} \quad T_2 = A + BE_2' + C(E_2')^2 .$$

$$\text{then } T_1 - T_2 = B(E_1 - E_2') + C(E_1^2 - E_2'^2)$$

$$\text{now} \quad E_2' = E_2 - \Delta E$$

and $E_1 = E_2 + \text{Diff.}$ ("Diff." is the reading of the differential couple.)

Substituting for E_1 and E_2' above

$$T_1 - T_2 = B(\text{Diff} + \Delta E) + C(\text{Diff} + \Delta E)(E_1 + E_2 - \Delta E)$$

ΔE is negligible in comparison with E_1 and E_2 and may be dropped from the last factor.

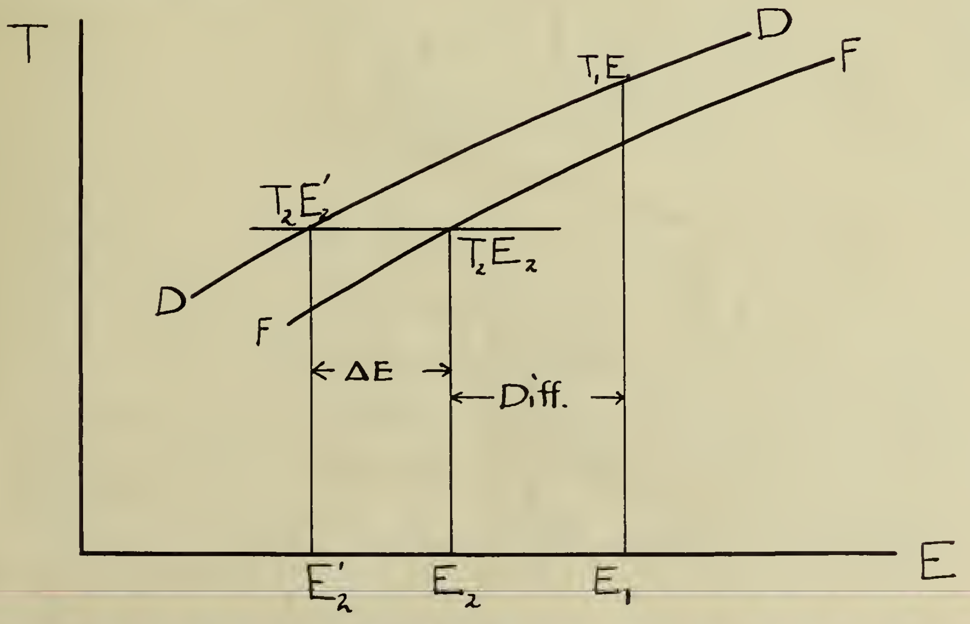
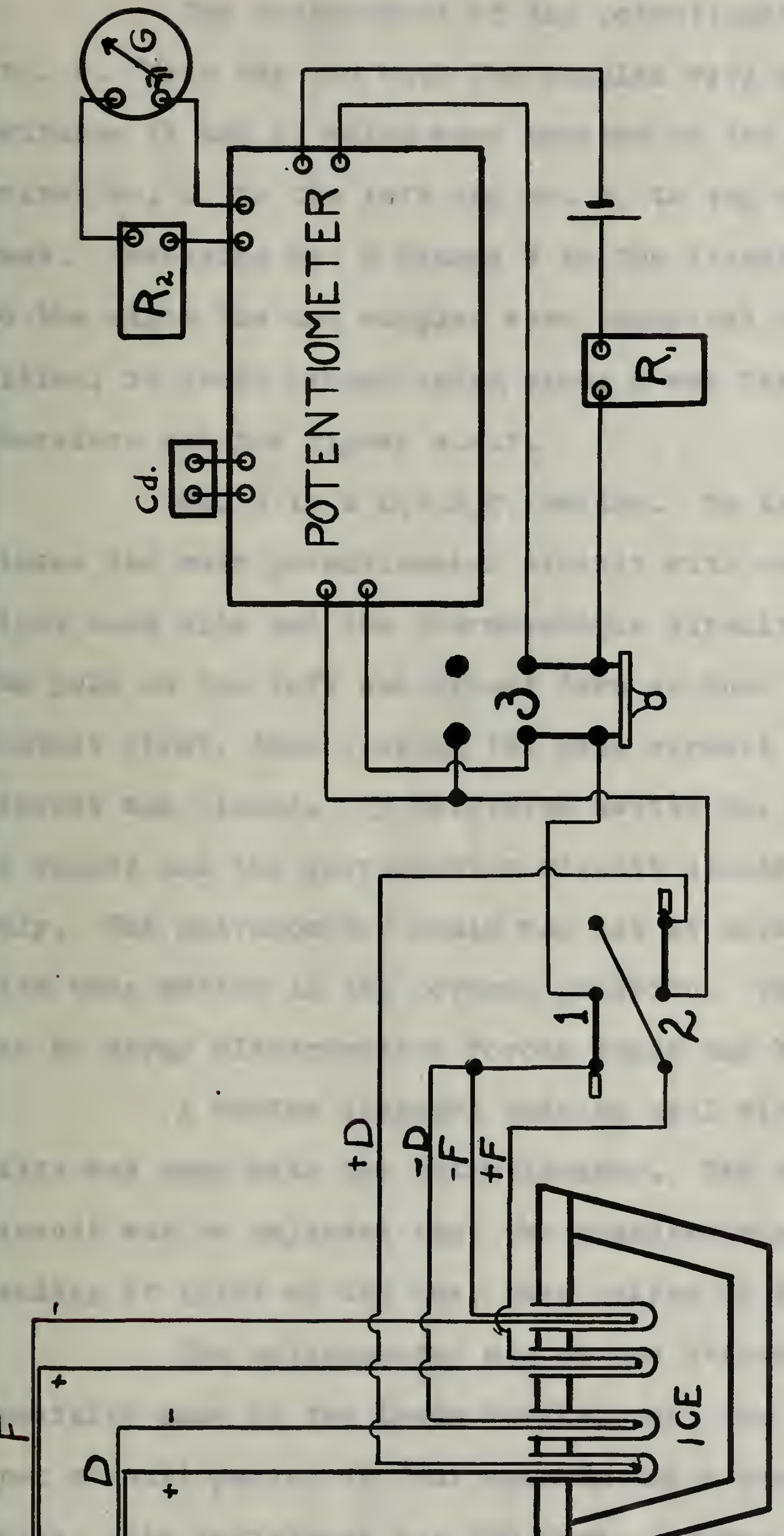


FIG. 4.

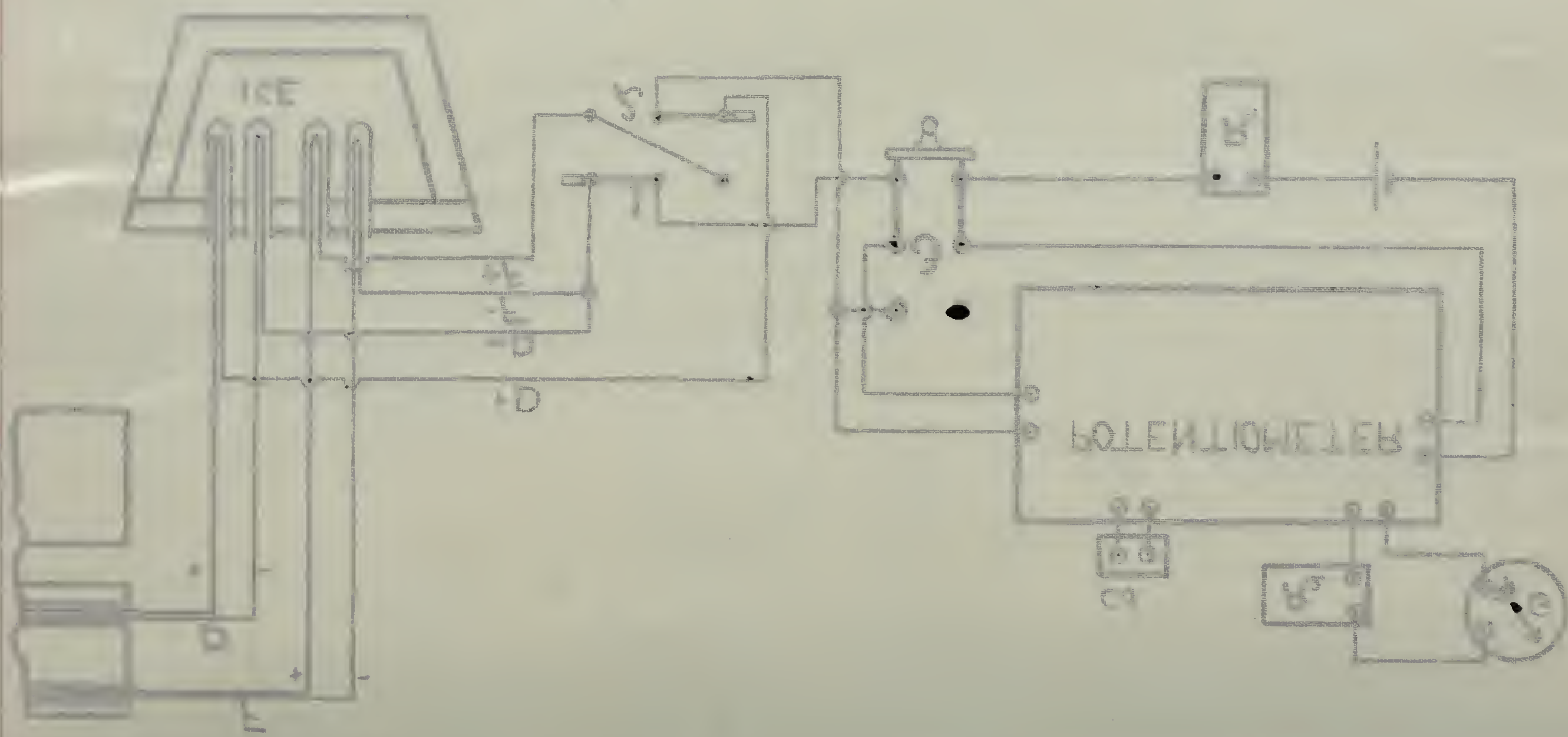


POTENTIOMETER CIRCUIT

FIG. 5

FIG. 3

POTENTIOMETER CIRCUIT



The arrangement of the potentiometer circuits is shown in Fig. 5. From the ice bath the couples were connected to two S.P.D.T. switches (1 and 2) which were mounted on the same base. Throwing switch No. 1, to the left and No. 2, to the right, couple D could be read. Reversing No. 2 placed F in the circuit. With both switches to the right the two couples were connected in the circuit in opposition, in their proper order, since D was the hotter couple and therefore had the higher e.m.f.

No. 3 is a D.P.D.T. switch. In the position shown it closes the main potentiometer circuit with one storage cell, on the right hand side and the thermo-couple circuit on the left hand side. The pole on the left was ground down so that the right side made contact first, thus closing the main circuit before the galvanometer circuit was closed. By reversing switch No. 3 the battery circuit is opened and the galvanometer circuit closed thru the potentiometer only. The galvanometer scale was set at zero before each reading with this switch in the reverse position. This eliminates errors due to stray electromotive forces which may be in the circuit.

A Weston standard cadmium cell with an e.m.f. of 1.0197 volts was used with the potentiometer. The resistance (R_1) in the circuit was so adjusted that the standard was just balanced by a reading of 1.0197 on the box, thus making it direct reading.

The galvanometer was of the D'Arsonval type and was specially made by the Leeds Northrup Co. for this work. It had an open circuit period of four seconds and a sensibility of 2.85 microvolts. Its resistance was 230 ohms. It was used with a telescope and scale at a distance of about 150 cm.

The resistance R_2 was so adjusted that one division on

the last dial of the Wolff box corresponded to ten divisions of the scale. One micro-volt,(about .1°C), then gave a deflection of one scale division. This was accomplished by first closing the battery circuit, setting the potentiometer on zero, and short circuiting the thermo-couple circuit. Such a value of R_2 could then be found that a movement of one division of the next to last dial on the box would give a deflection of exactly one hundred scale divisions. Of course as the setting of the box is increased or diminished, R_2 would have to be decreased or increased a corresponding amount to keep the sensibility constant.

The scale used with the galvanometer was made by W. and L. E. Gurley, and had divisions about 0.6mm in length. One half of the scale was marked with red and was numbered from 800 at the end to 1000 or 0 at the center. The other half was black and was numbered from 0 at the center to 200 at the other end. The galvanometer was so connected that readings on the black were to be added to the potentiometer reading, and those on the red were to be subtracted from it. The advantage of having the red scale read backwards is that negative deflections are already subtracted when read, and the chance of error in this direction reduced to a minimum.

The statement was made above that the heat which was generated at the middle of the coil flowed out along radial lines. This assumption was tested by moving the outer couple (F, Fig. 2) back and forth in a longitudinal direction and noting the reading. This operation showed that the temperature was constant to 0.3°C for a distance of six or seven centimeters from the middle. As no heat will flow along constant temperature lines there could be no longitudinal flow of heat in the twelve or fourteen centimeters in the

middle of the test piece and the assumption is allowable.

The general method of operation was to start the furnace with a rather large current, about twenty-five amperes, and gradually reduce this as the furnace approached the temperature desired. This took from three to five hours for the lower temperatures. The storage battery would then be placed in the circuit (See Fig. 3), and the current kept constant for two or three hours more. When the outer couple, F, showed a temperature constant to one tenth of a degree, indicating equilibrium conditions, readings were taken. The voltage and current readings were taken before and after the temperature readings, in order to be sure there was no change. Readings were taken in order, of D, F, D, (D - F), and D. It will be noticed by referring to Fig. 5, that only one change of either switch No. 1, or No. 2, is necessary to change from any one of the above readings to the next in order.

Each cylinder, at the close of the tests on it, was broken across the middle and r_1 and r_2 carefully measured in the plane in which the temperature readings had been taken.

Five cylinders, made by the "Laclede-Christy Clay Products Co.", of St. Louis, were tested. The results of these tests are shown in tables 1 to 5, and also in the curves 1 to 5. The test pieces were simply numbered in the order tested. The readings in the tables are arranged in the order of ascending temperatures and not in the order in which they were taken. The temperatures plotted in the curves are the average temperatures given in column six of the tables 1 - 5.

Cylinder No. 1, was of medium coarse structure. It had a reddish, sandy appearance, with very small pieces of white gravel thruout its mass.

Cylinder No. 2, was very coarse and almost white. It contained a large number of small gravel stones.

No. 3 was a dark reddish, brown color and contained no gravel. It had the appearance of sandstone. The piece was cracked in a great many places after the test, due to the heating.

No. 4 was very similar in appearance to No. 2, tho it will be noticed that the curves of the two cylinders are different.

No. 5 was similar to No. 1, tho somewhat coarser.

At the time of writing this paper no information was obtainable concerning the exact composition of the various pieces tested.

Table No. 6 shows the comparative values of K for the different specimens. These values are taken from the curves as shown.

The accuracy of the values for K in this work is limited to that of r_1 and r_2. The temperature readings are certainly accurate to 1.0°C, and very probably to 0.5°C. The voltage and current

readings are accurate to one percent. An error may be introduced in the values of r_1 and r_2 because of the uncertainty of the position of the thermo-junction in the hole. If the couple were touching one side of the hole it would take the temperature of that side, while r_1 and r_2 were always measured to the center of the holes. This error, however, would be a constant factor for the tests on any cylinder, for the couples were never disturbed after they were once placed in a cylinder, until the completion of the tests on that piece. Thus the comparative values of K for any given specimen at different temperatures would not be affected by the values of r_1 and r_2.

The greatest error is caused by changes of current thru the furnace. The supply voltage changed a great deal and the batteries used were not large enough to maintain the current constant at all times. If the current should change just before a reading was taken, the temperatures would not correspond to the other readings altho they were not changing at the time. The wide variation between cylinders No. 1, and 5, and between Nos. 2 and 4 is probably due to a difference in porosity. An investigation of the effect of porosity as well as composition of substances would no doubt lead to more definite results, in regard to a comparison of fire clays. The results of this work, however, should give more definite knowledge of the loss of heat thru furnace walls, which was its primary object.

E	I	T_1	T_2	$T_{diff.}$	$\frac{1}{2}(T_1+T_2)$	K
24.0	15.1	300.0	263.0	38.2	281.5	.00186
24.4	15.5	305.1	266.9	39.3	286.0	.00188
27.8	16.7	366.1	317.8	49.1	341.9	.00185
28.8	16.9	375.4	325.8	50.4	350.6	.00189
32.8	18.3	418.3	360.0	58.7	389.1	.00190
33.3	18.4	428.6	366.3	63.0	397.5	.00191
35.4	18.9	472.9	403.4	70.1	438.1	.00187
40.3	20.2	526.2	444.2	82.5	485.2	.00193
47.7	21.2	622.0	522.0	100.6	572.0	.00196

TABLE No.1.

E	I	T_1	T_2	$T_{diff.}$	$\frac{1}{2}(T_1+T_2)$	K
30.1	17.8	447.3	365.7	81.3	406.5	.00264
36.3	19.8	547.6	438.9	108.4	493.2	.00266
36.0	19.8	551.8	443.6	108.0	497.7	.00265
40.0	20.9	620.6	494.5	126.0	557.5	.00266
40.9	21.1	629.5	501.4	128.1	565.4	.00270
43.9	21.7	678.9	532.5	146.3	605.7	.00261
46.3	22.0	732.8	577.6	155.4	655.2	.00267
47.3	22.3	736.5	577.7	158.6	657.1	.00263
50.6	22.5	791.1	618.1	172.9	704.6	.00264

TABLE No.2.

E	I	T_1	T_2	$T_{diff.}$	$\frac{1}{2}(T_1 + T_2)$	K
39.2	19.9	598.3	394.1	203.3	496.2	.00245
43.8	19.0	659.9	443.5	216.4	551.6	.00245
45.5	20.7	710.0	473.5	236.0	591.7	.00254
49.7	20.4	764.6	501.4	263.0	633.0	.00246
51.7	20.3	797.7	526.5	271.0	662.1	.00247
52.7	20.2	799.8	529.7	270.4	664.7	.00251
52.8	20.5	806.8	538.3	268.5	672.6	.00257
59.7	20.8	894.3	581.7	312.4	738.0	.00252
61.0	21.0	899.9	585.3	314.9	742.6	.00259
61.8	20.6	917.1	597.4	319.7	757.2	.00254

TABLE No. 3.

E	I	T_1	T_2	$T_{diff.}$	$\frac{1}{2}(T_1 + T_2)$	K
31.0	17.4	463.1	380.8	81.9	421.9	.00273
34.3	18.3	510.3	418.8	91.3	464.6	.00285
42.0	20.5	641.6	521.0	119.6	581.3	.00299
57.8	21.9	898.7	729.9	168.3	814.3	.00312
63.8	21.8	970.2	783.1	187.0	875.7	.00309
64.8	21.0	976.2	789.2	186.7	882.7	.00302

TABLE No. 4.

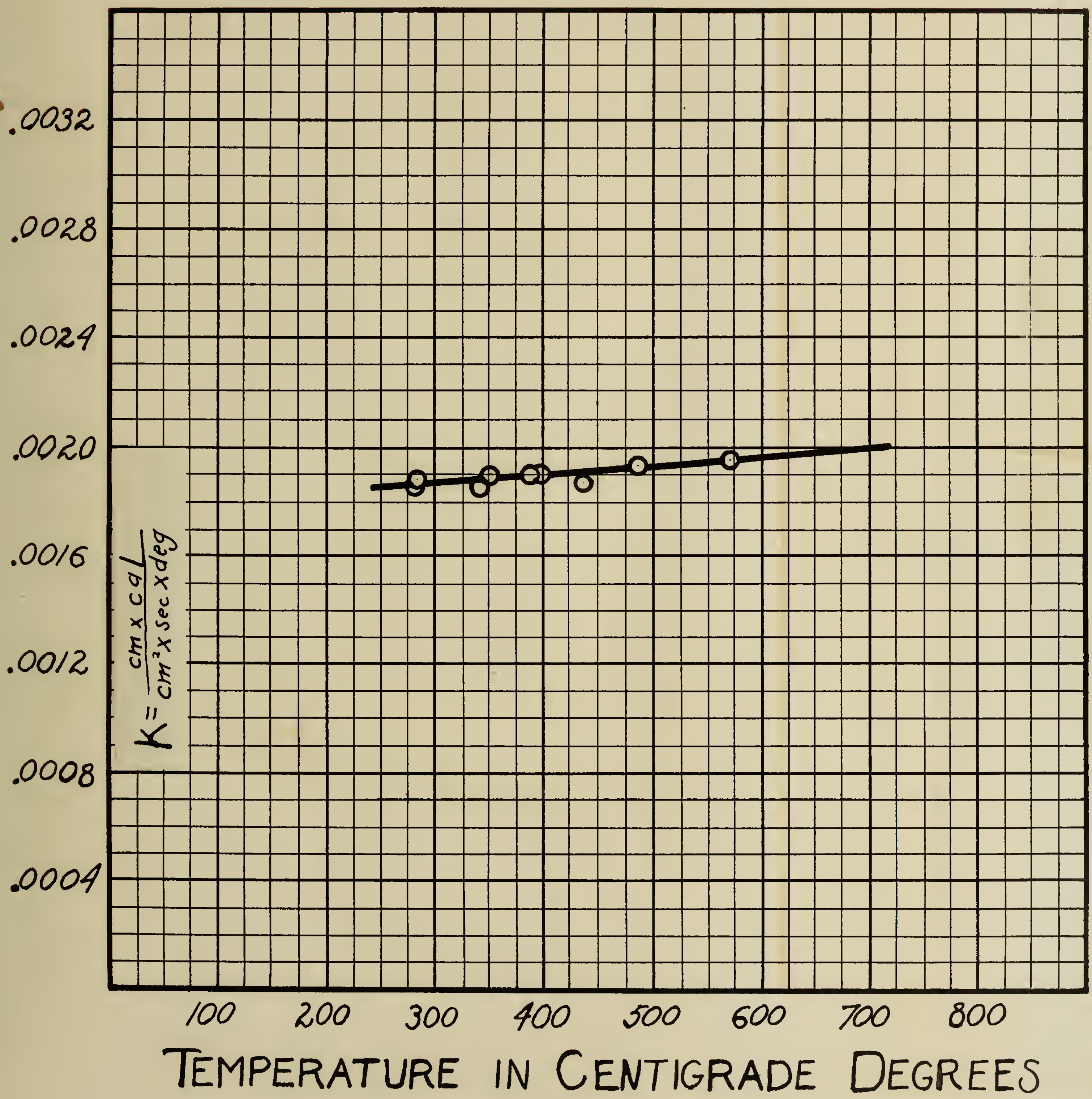
E	I	T_1	T_2	Tdiff.	$\frac{1}{2}(T_1+T_2)$	K
29.6	16.8	434.1	342.3	91.6	388.2	.00366
34.8	18.4	533.5	414.5	118.5	474.0	.00364
42.6	20.5	679.7	513.7	165.7	596.7	.00355
45.2	21.2	717.9	536.8	180.7	627.4	.00358
54.3	22.8	871.6	641.4	230.2	756.5	.00362

TABLE No. 5.

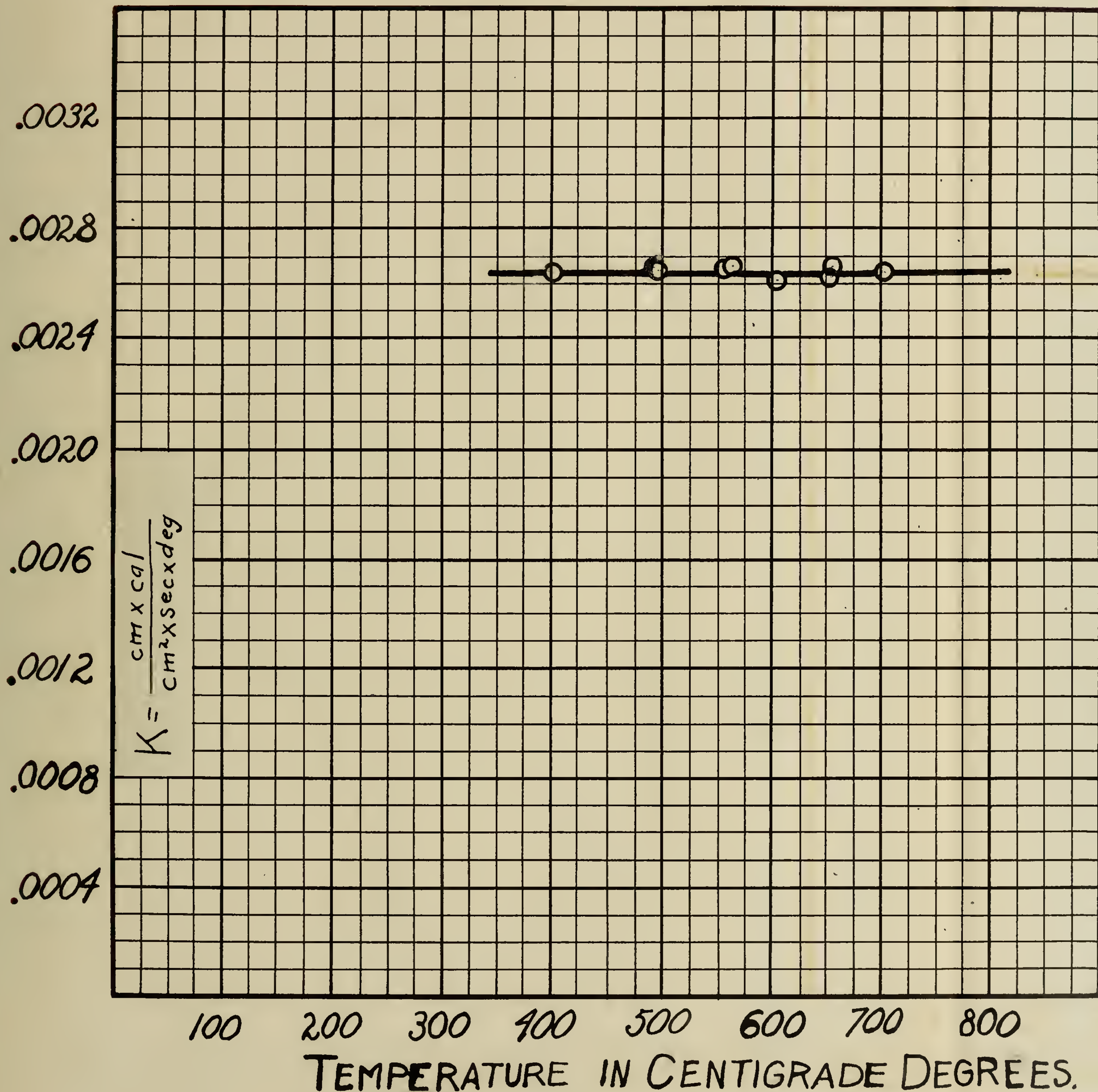
No. of Cyl.	400°	500°	600°	700°	800°
1.	.00190	.00193	.00197	....	....
2.	.00264	00264	.00264	.00264	.00264
3.	.00241	.00246	.00250	.00254	.00259
4.	.00275	.00284	.00294	.00303	.00310
5.	.00360	.00360	.00360	.00360	.00360

TABLE No. 6.

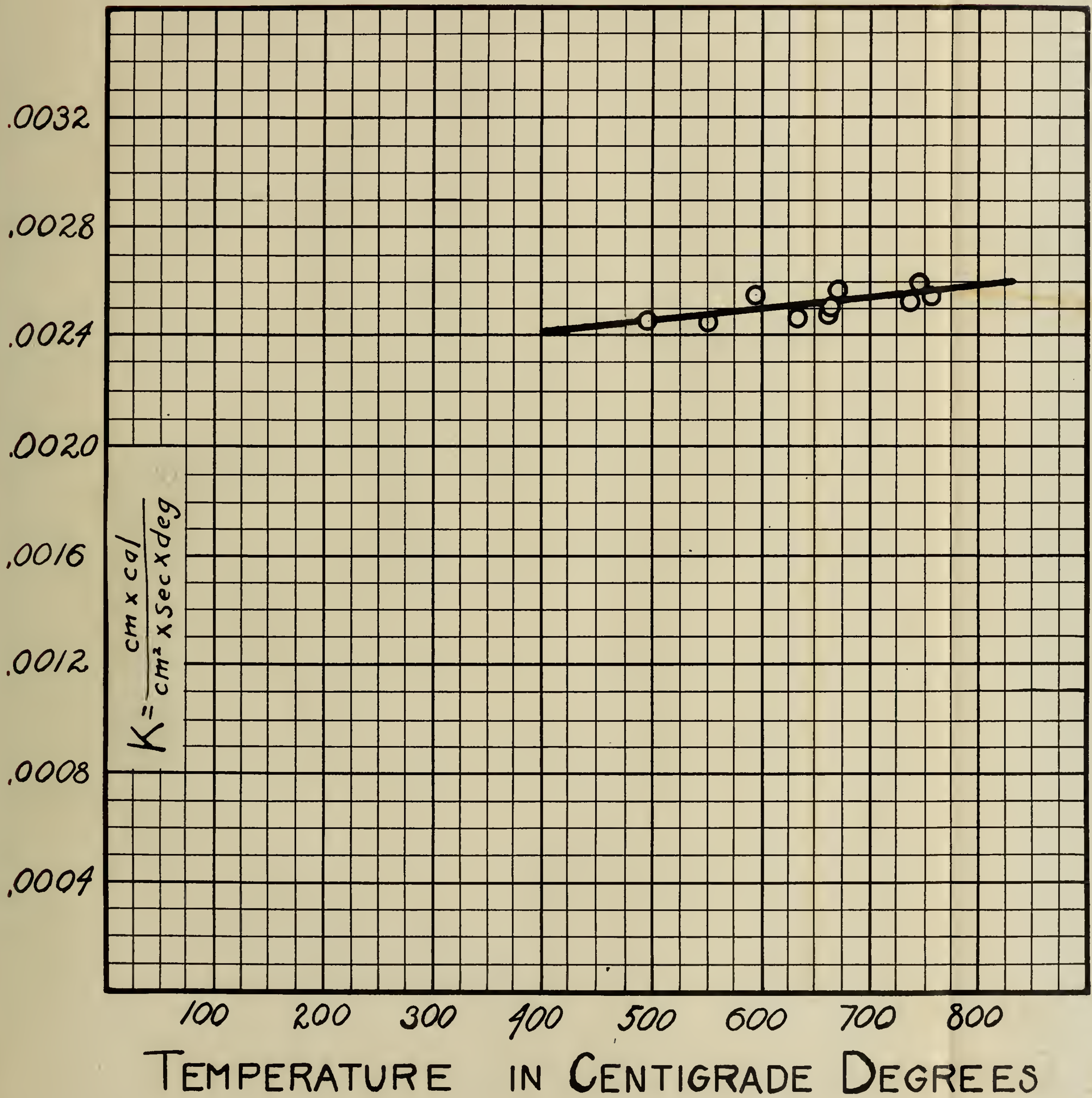
CYLINDER No. 1.



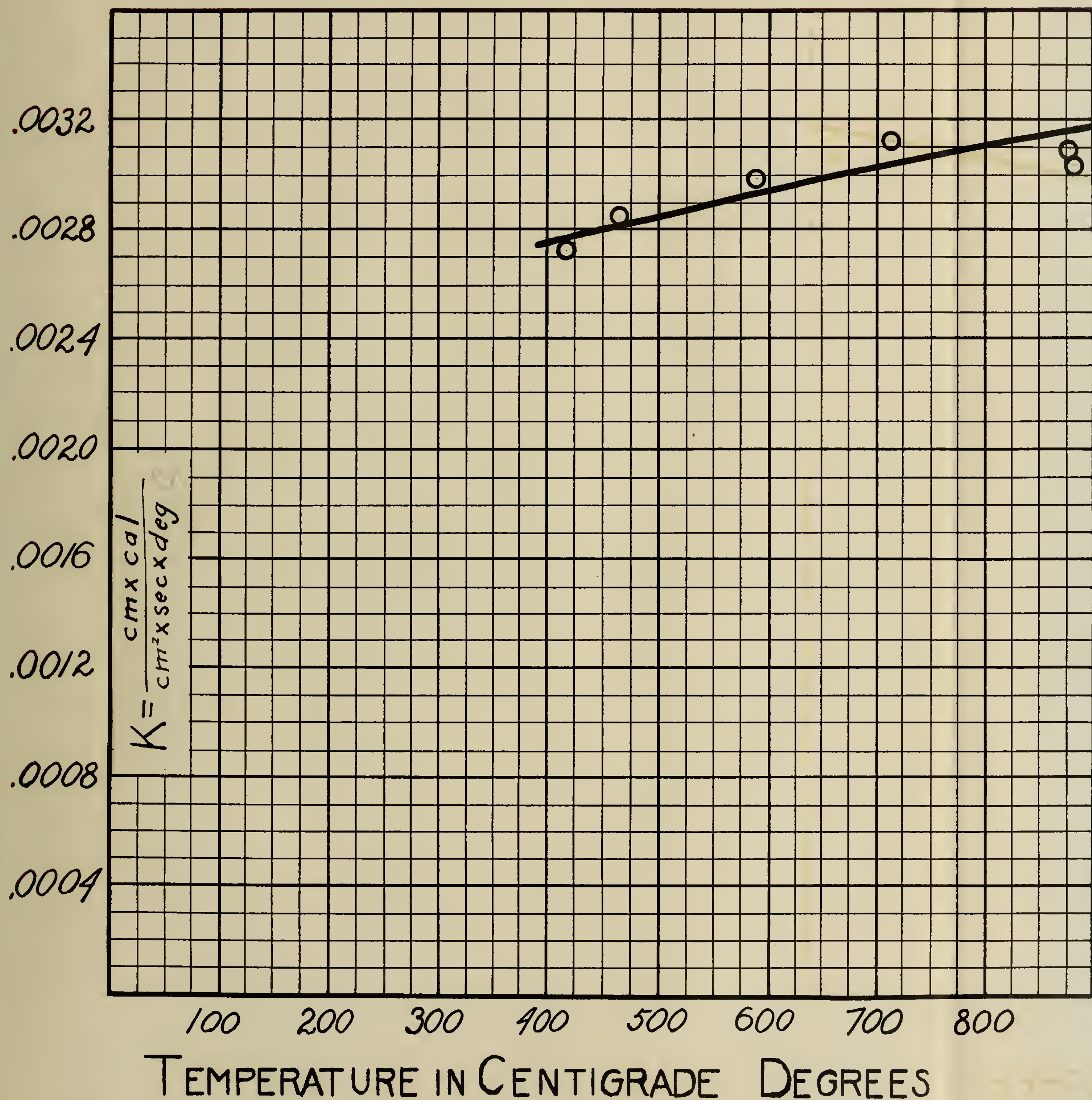
CYLINDER No.2.

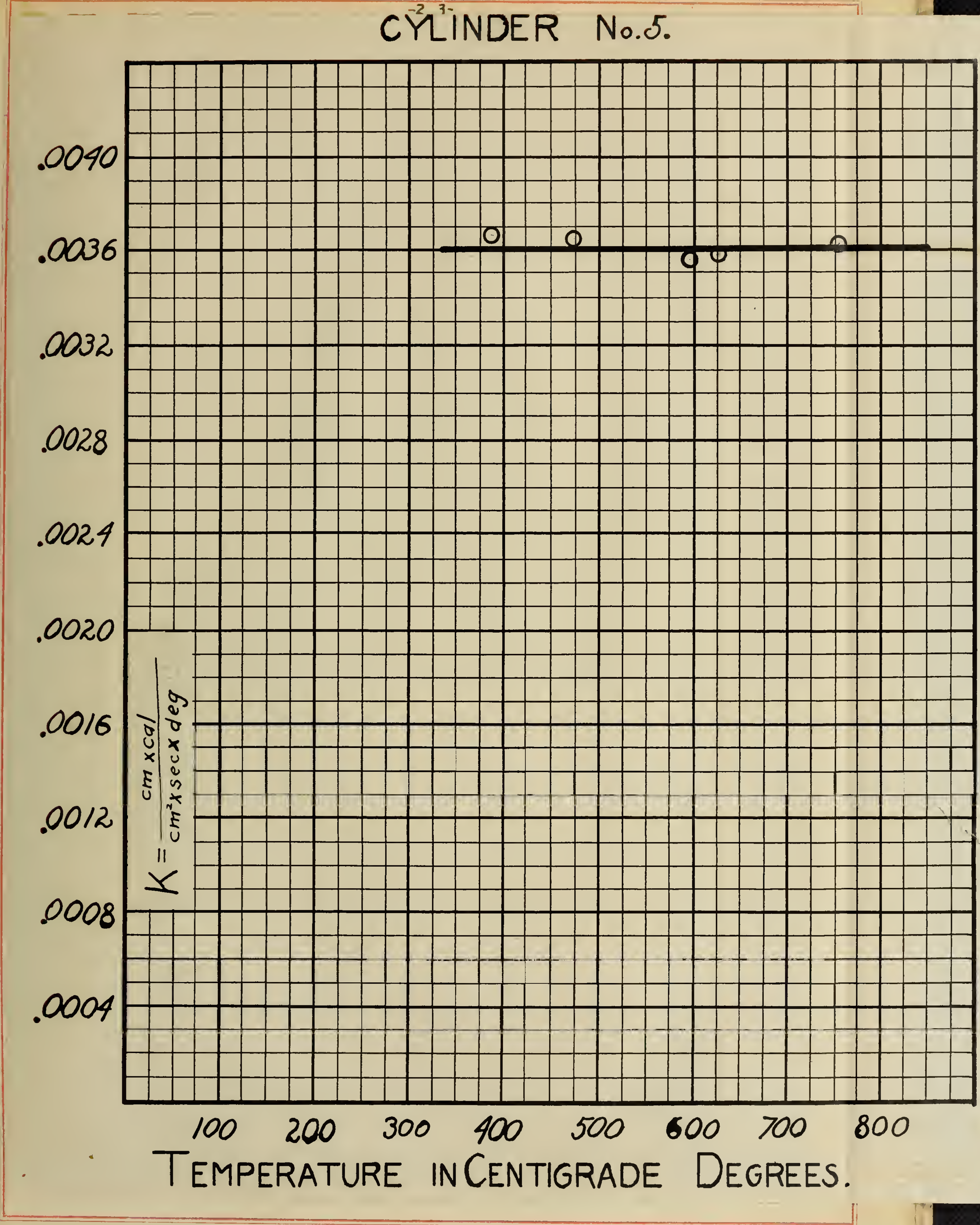


CYLINDER No. 3.



CYLINDER No. 4.





CYLINDER No. 5.
.0040
.0036
.0032
.0028
.0024
.0020
.0016
.0012
.0008
.0004
$K = \frac{cm \times cal}{cm^2 \times sec \times deg}$
100
200
300
400
500
600
700
800
TEMPERATURE IN CENTIGRADE DEGREES.

REFERENCES.

E. H. Hall - Phys. Rev. Vol. X. p. 277.
June, 1900.

Holborn & Wien - Zeitschr, Ver. Deutsch.
Ingen., Vol. 40, 1896.

Herschel, Lebour, & Dunn.
Rep. Brit. Assoc. Vol. 49, 1879.

Lees & Chorlton - Phil. Mag. Vol. 41, Ser. 5.
1896 - pp. 495.

G. Glage - Ann. d. Physik. Vol. 323,
Dec. 1905 - pp. 904.

C. Niven - Roy. Soc. Proc. Vol. 76 A
April 22,'05. pp. 34.

Tait - Trans. Roy. Soc. Edin.
Vol. 28, p. 717, 1879.

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